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Funayama

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(54) **MAGNETIC DISK APPARATUS**

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G11B 5/02 (2006.01)

(52) **U.S. Cl.**
USPC **360/68**; 360/46

(58) **Field of Classification Search**
None
See application file for complete search history.

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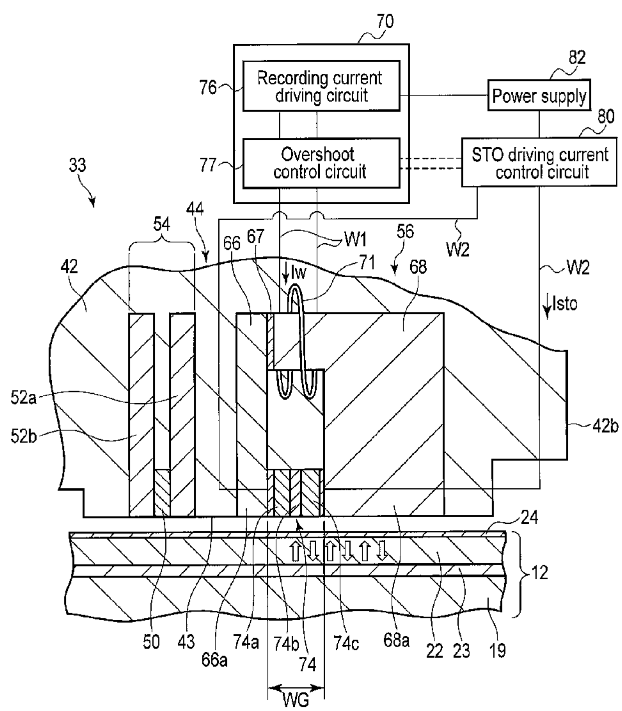
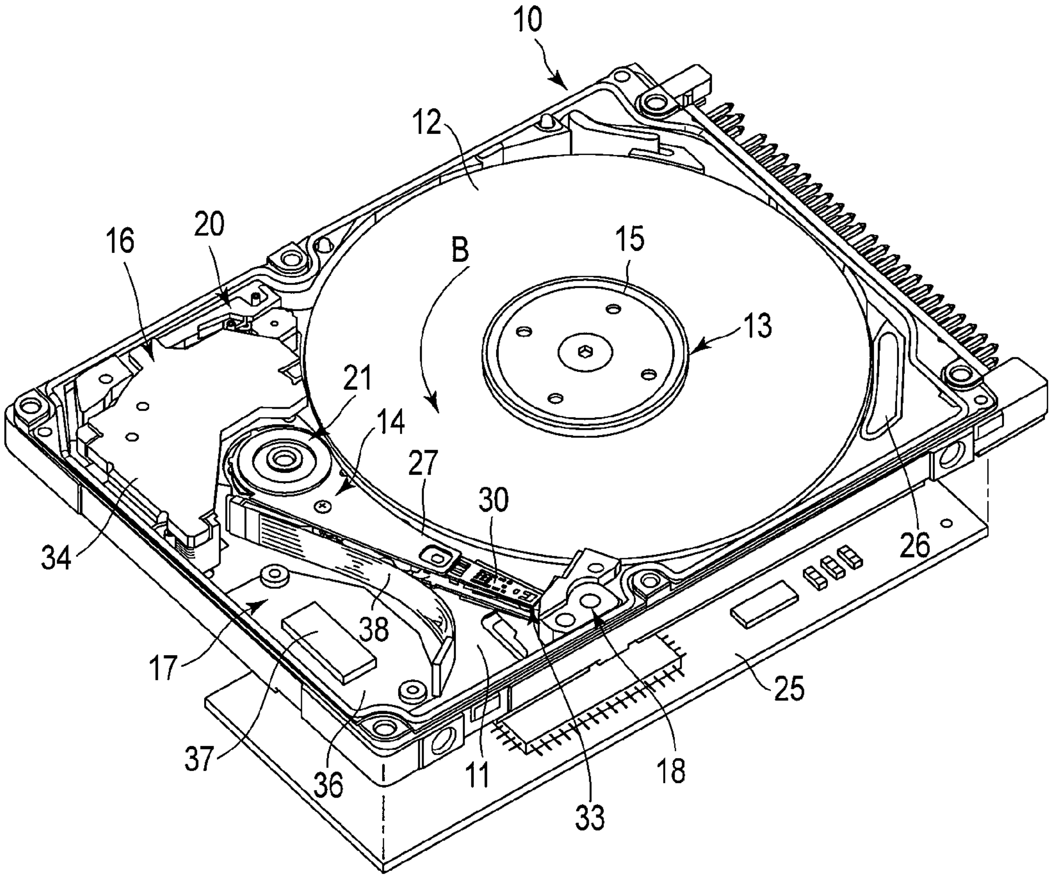
(57) **ABSTRACT**

According to one embodiment, a magnetic disk apparatus includes a main magnetic pole configured to apply a recording magnetic field to a recording medium, a recording coil configured to magnetize the main magnetic pole, a spin-torque oscillator adjacent to the main magnetic pole, and configured to generate a high frequency magnetic field, a recording current control circuit configured to supply a recording current to the recording coil, a driving current control circuit configured to supply a fixed driving current to the spin-torque oscillator, and an overshoot control circuit configured to control overshoot current of the recording current in proportion to the magnitude of the driving current after the recording current has reversed.

13 Claims, 5 Drawing Sheets

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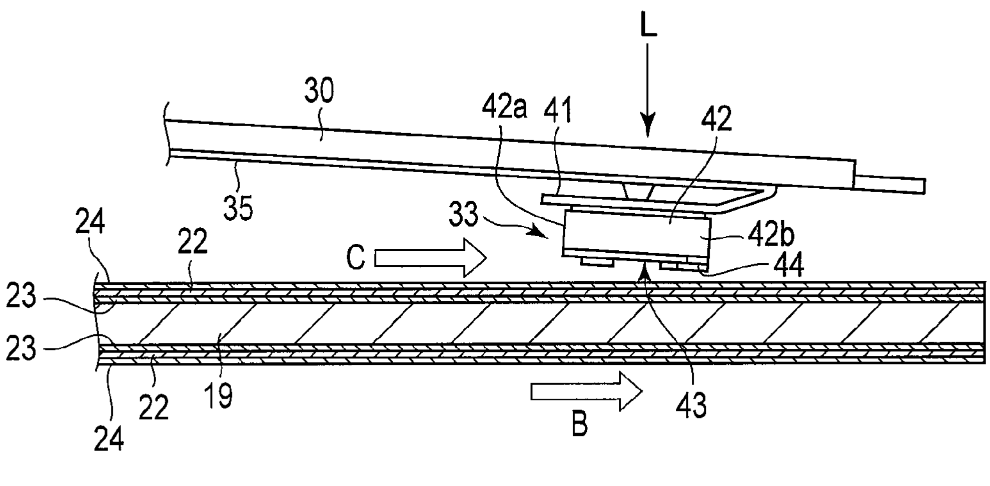
F I G. 1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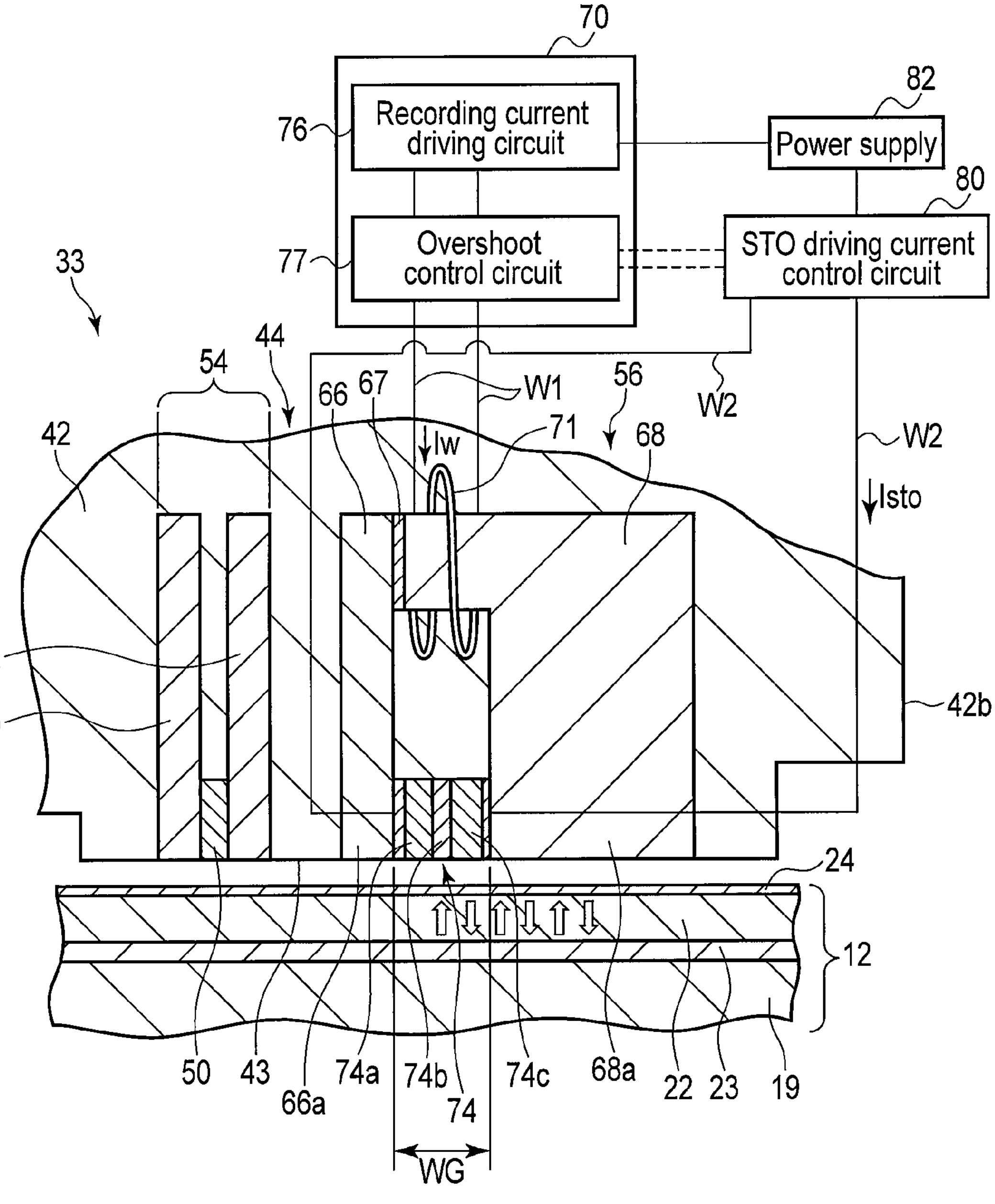
F I G. 2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Recording current driving circuit
76
82
Power supply
80
Overshoot control circuit
77
STO driving current control circuit
33
54
44
66
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W2
42
71
68
W2
Iw
Isto
52a
52b
42b
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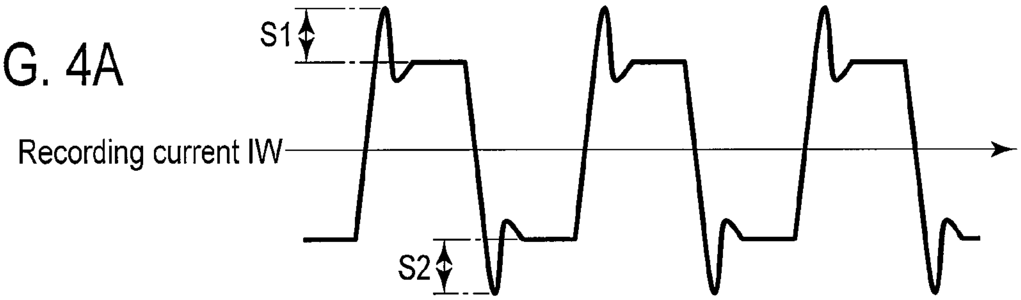
19
WG

F I G. 3

F I G. 4A



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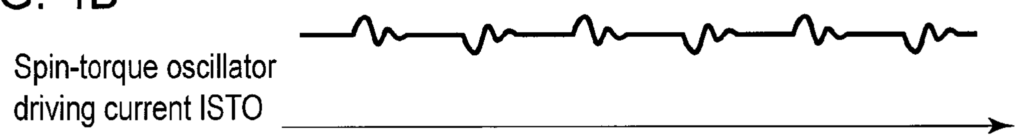

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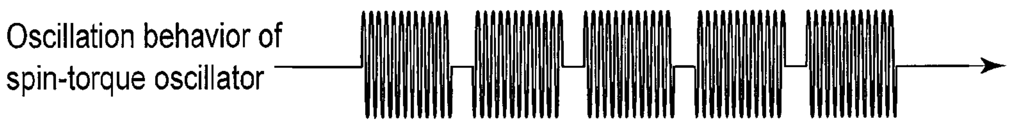

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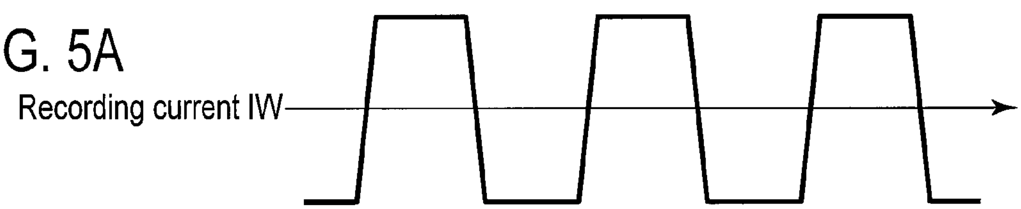

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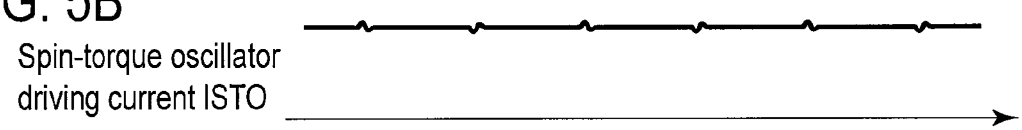

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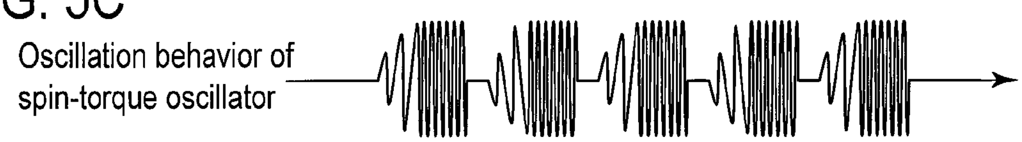

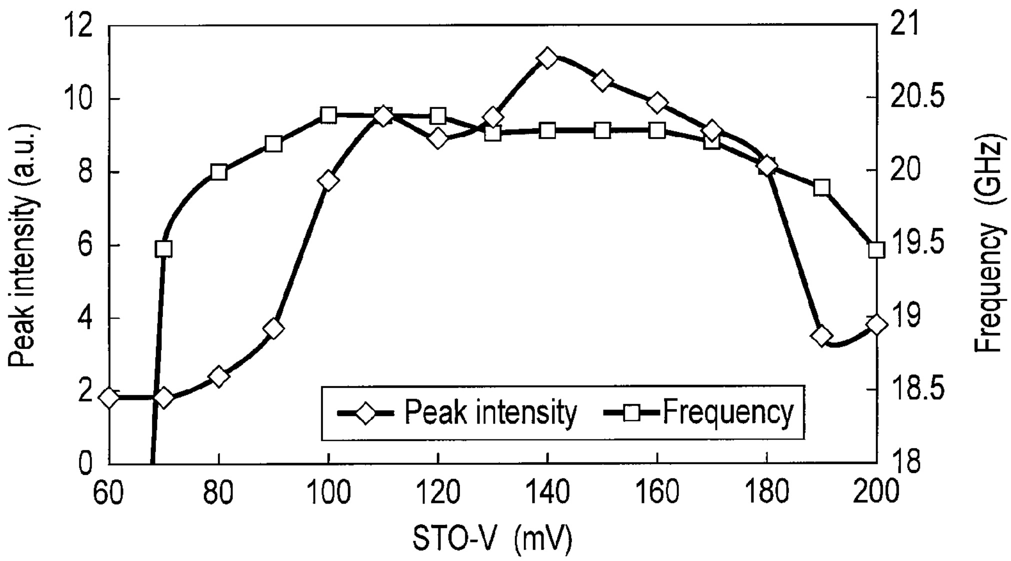
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Frequency (GHz)
STO-V (mV)
Peak intensity
Frequency
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6
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21
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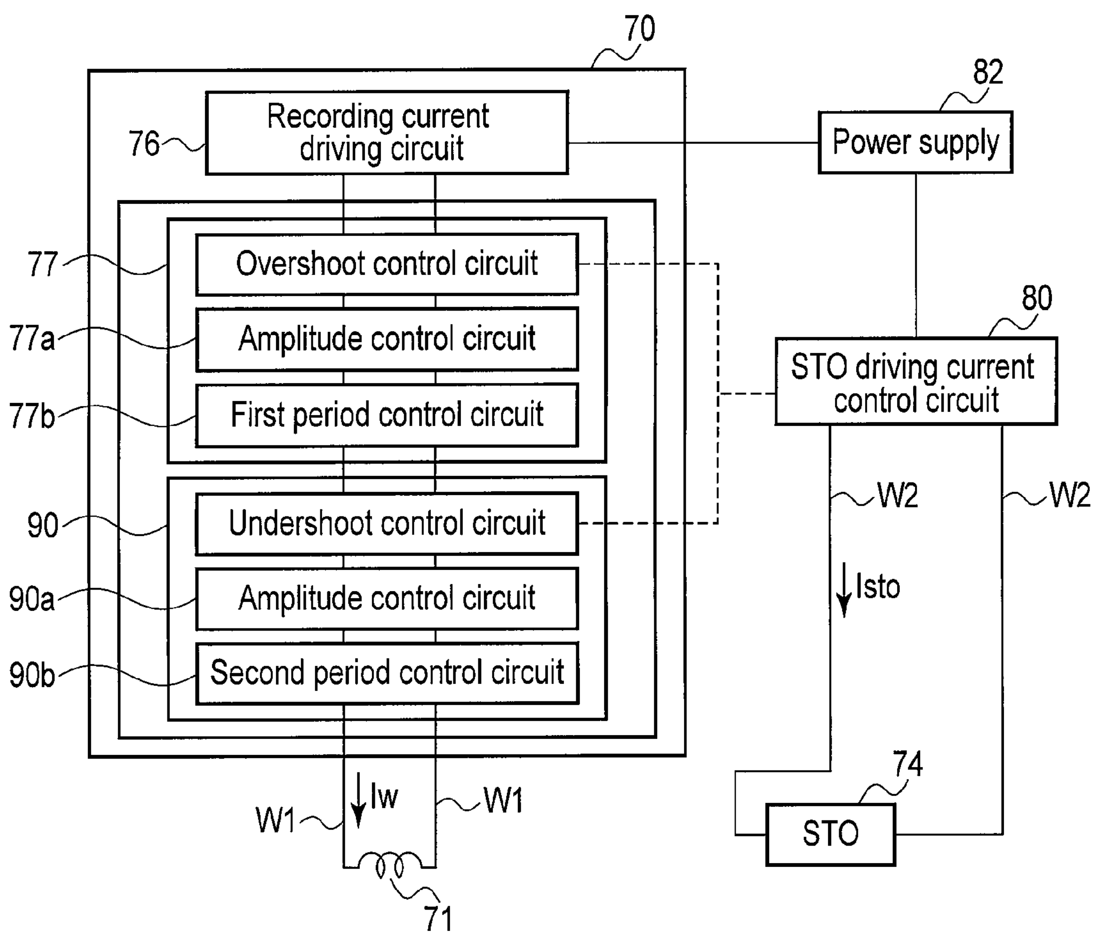
F I G. 6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90a
Amplitude control circuit
90b
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W2
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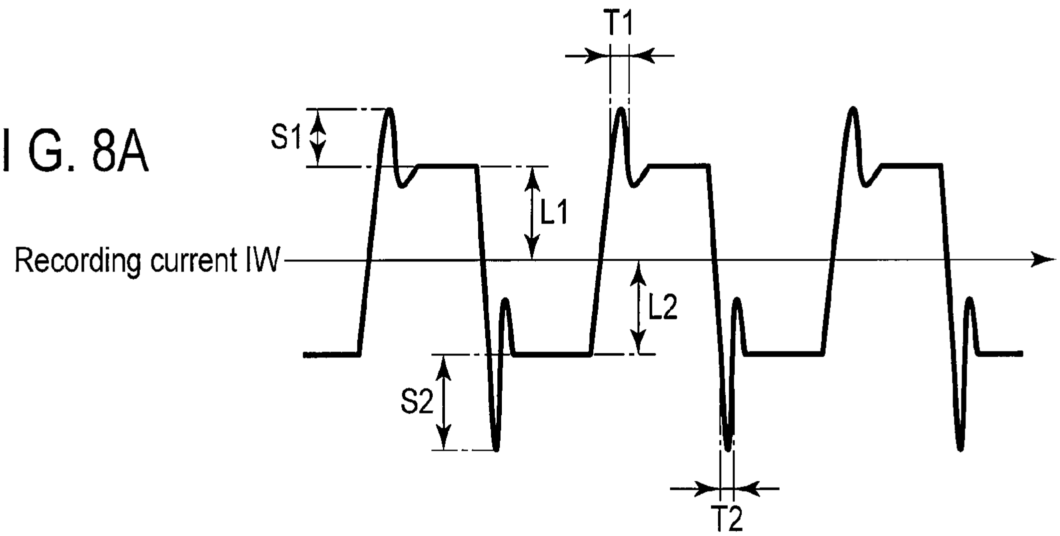
W1
W1
74
STO
71

F I G. 7

F I G. 8A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L2
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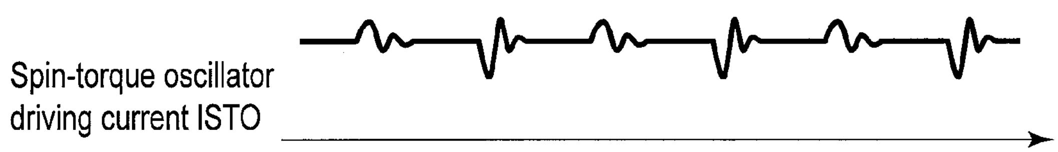
Spin-torque oscillator
driving current ISTO

MAGNETIC DISK APPARATUS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is based upon and claims the benefit of priority from Japanese Patent Application No. 2014-134094, filed Jun. 30, 2014, the entire contents of which are incorporated herein by reference.

FIELD

Embodiments described herein relate generally to a magnetic disk apparatus employing a microwave assist system.

BACKGROUND

A magnetic disk apparatus as an example of a disk apparatus incorporates a magnetic disk in a case, a spindle motor which supports and rotates the magnetic disk, and a magnetic head for reading/writing data from/to the magnetic disk.

In recent years, a magnetic head employing a microwave assist recording system is proposed for the purpose of improving recording density, in which a spin-torque oscillator is provided as a microwave oscillator near the main magnetic pole of the magnetic head and a high-frequency magnetic field is applied from the spin-torque oscillator to the magnetic recording layer of the magnetic disk. Furthermore, a magnetic disk apparatus employing a drive control system is proposed, in which a drive signal in a first level, which is a fixed or steady level, is continuously supplied to the spin-torque oscillator, and a drive signal in a second level, which is higher than the first level, is supplied to the spin-torque oscillator for a predetermined time after the recording signal has reversed in polarity.

However, it may happen that a high voltage should be unexpectedly applied to the spin-torque oscillator due to switching noises or the like while making rapid changes between a drive signal of the first level and a drive signal of the second level, causing the oscillations of the spin-torque oscillator to be unstable. In the worst case, the spin-torque oscillator will be damaged.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a perspective view of a magnetic disk apparatus (HDD) related to a first embodiment;

FIG. **2** is a side view of the HDD, illustrating a magnetic head, a suspension, and a recording medium;

FIG. **3** is a sectional view schematically illustrating in an enlarged manner the head portion of the magnetic head and a portion of the magnetic disk;

FIG. **4**A is a graph illustrating a recording current waveform of the magnetic head;

FIG. **4**B is a graph illustrating a spin-torque oscillator driving current waveform of the magnetic head;

FIG. **4**C is a graph illustrating an oscillation behavior of the spin-torque oscillator;

FIG. **5**A is a graph illustrating a recording current waveform of a magnetic head in a comparative example;

FIG. **5**B is a graph illustrating a spin-torque oscillator driving current waveform of the magnetic head in the comparative example;

FIG. **5**C is a graph illustrating an oscillation behavior of the spin-torque oscillator in the magnetic head in the comparative example;

FIG. **6** is a view illustrating the relationship between the oscillation intensity and the oscillation frequency in a case where the oscillation behavior of the spin-torque oscillator is measured under the condition that the driving current is changed in the first embodiment;

FIG. **7** is a block diagram illustrating an overshoot control circuit of a magnetic disk apparatus related to a second embodiment;

FIG. **8**A is a graph illustrating a recording current waveform of a magnetic head in the second embodiment; and

FIG. **8**B is a graph illustrating a spin-torque oscillator driving current waveform of the magnetic head in the second embodiment.

DETAILED DESCRIPTION

Various embodiments will be described hereinafter with reference to the accompanying drawings. According to one embodiment, a magnetic disk apparatus generally comprises a main magnetic pole configured to apply a recording magnetic field to a recording layer of a recording medium; a recording coil configured to magnetize the main magnetic pole; a spin-torque oscillator, configured to generate a high frequency magnetic field, adjacent to the main magnetic pole and close to a medium-facing surface opposite the recording medium; a recording current control circuit configured to supply a recording current to the recording coil; a driving current control circuit configured to supply a fixed driving current to the spin-torque oscillator; and an overshoot control circuit configured to control, in proportion to a magnitude of the driving current, overshoot current of the recording current occurring after the recording current has reversed.

Now, a hard disk drive (HDD) related to an embodiment will be taken up as a magnetic disk apparatus and will be explained in detail with reference to the drawings.

First Embodiment

FIG. **1** illustrates an HDD according to a first embodiment with a top cover removed to reveal its internal configuration, and FIG. **2** illustrates a magnetic head in a flying state. As illustrated in FIG. **1**, the HDD comprises a housing **10**. The housing **10** comprises a box-shaped base **11**, whose upper end is open, and a rectangular plate-shaped top cover, which is not illustrated in the drawings. The top cover is screwed to the base with screws to close the open upper end of the base. As a result, the inside of the housing **10** is air-tightly maintained and can communicate with the outside for ventilation through a breather filter **26** alone.

A drive section and a magnetic disk **12** working as a recording medium are provided on the base **11**. The drive section comprises a spindle motor **13** that supports and rotates the magnetic disk **12**, a plurality (for example, two) of magnetic heads **33** that record and reproduce data on and from the magnetic disk **12**, a head actuator **14** that supports the magnetic heads **33** for movement relative to the respective surfaces of the magnetic disk **12**, and a voice coil motor (VCM) **16** that rotationally moves and positions the head actuator **14**. Further, on the base **11** are provided a ramp loading mechanism **18** that holds each of the magnetic heads **33** in a position off the magnetic disk **12** when the magnetic heads **33** are moved to the outermost periphery of the magnetic disk **12**, an inertia latch mechanism **20** that holds the head actuator **14** in a retracted position if the HDD is jolted, for example, and a board unit **17** having electronic components, including a conversion connector **37**, for instance, mounted thereon.

A control circuit board **25** is screwed to the outer surface of the base **11**, facing the bottom wall of the base **11**. The control circuit board **25** controls through the board unit **17** the operation of the spindle motor **13**, that of the VCM **16**, and that of the magnetic heads **33**.

As illustrated in FIG. **1** and FIG. **2**, the magnetic disk **12** is made as a perpendicular magnetic recording medium. The magnetic disk **12** comprises, for instance, a substrate **19** which is made of a non-magnetic material and is shaped into a circular plate having a diameter of 2.5 inches (6.35 cm). On each surface of the substrate **19**, a soft magnetic layer **23**, serving as a foundation layer, a magnetic recording layer **22** and a protective film **24**, both forming an upper layer portion, are successively stacked in this order.

As illustrated in FIG. **1**, the magnetic disk **12** is fitted on the hub of the spindle motor **13** to be coaxial with the hub, is tightly held by a clamp spring **15** screwed to the upper end of the hub, and thereby is fixed to the hub. The magnetic disk **12** is made to rotate in a direction of an arrow B at a predetermined speed by the spindle motor **13** working as a drive motor.

As illustrated in FIG. **1** and FIG. **2**, the head actuator **14** comprises a bearing portion **21** fixed on the bottom wall of the base **11**, and arms **27** extending from the bearing portion **21**. The arms **27** are located with a predetermined distance put in between, are in parallel with the surfaces of the magnetic disk **12**, and extend in the same direction from the bearing portion **21**. The head actuator **14** includes elastically deformable elongated sheet-shaped suspensions **30**. The suspensions **30** individually have a proximal end that is fixed by spot welding or bonding to a corresponding one of the distal ends of the arms **27**, so that they extend from the respective arms **27**. The magnetic heads **33** are fixed through gimbal springs **41** to the distal ends of the suspensions **30**. It should be noted that the head actuator **14** may be formed to have a so called E-block structure, in which the sleeve of the bearing portion **21** and the arms are formed as a single unitary body.

As illustrated in FIG. **2**, each of the magnetic heads **33** comprises a slider **42** in the shape of a nearly rectangular parallelepiped and a head portion **44** for recording/reproducing provided at the outflow end (the trailing end) of the slider **42**. The two arms **27** are parallel with each other with a predetermined distance therebetween. The suspensions **30** and the magnetic heads **33** attached to the arms **27** face the respective counterparts, with the magnetic disk **12** held in between.

Each of the magnetic heads **33** is electrically connected to the board unit **17** and the control circuit board **25** through a main FPC **38** of the board unit **17** and a relay flexible printed circuit board (an interconnection member) **35** fixedly extending over a corresponding one of the suspensions **30** and a corresponding one of the arms **27**.

As illustrated in FIG. **1**, the VCM **16** has a non-illustrated support frame, which extends from the bearing portion **21** in a direction opposite to the arms **27**, and a voice coil supported by the support frame. In a condition that the head actuator **14** is incorporated in the base **11**, the voice coil is between a pair of yokes **34** fixed on the base **11**, and constitutes the VCM **16** along with the yokes and magnets fixed to the yokes.

The energization of the voice coil of VCM **16** while the magnetic disk **12** is rotating causes the head actuator **14** to rotationally move and the magnetic head **33** to move to be located on a desired track on the magnetic disk **12**. At this moment, the magnetic head **33** radially moves over the magnetic disk **12** between its inner peripheral portion and its outer peripheral portion.

Now, the structure of the magnetic head **30** will be explained in detail. FIG. **3** is a sectional view illustrating in an enlarged manner the head portion **44** of the magnetic head **33** and a portion of the magnetic disk.

As illustrated in FIG. **2** and FIG. **3**, the magnetic head **33** is structured as a flying type head, and comprises a slider **42** and a head portion **44**. The slider **42** is formed of, for example, a sintered compact (AlTiC) of alumina and a titanium carbide. The head portion **44** is formed of layers of thin films.

The slider **42** has a rectangular disk facing surface (a medium facing surface, an air bearing surface [ABS]) **43** facing one surface of the magnetic disk **12**. The slider **42** is kept flying by a predetermined amount from the surface of the magnetic disk **12** due to an air flow C generated between the disk surface and the disk facing surface **43** by the rotation of the magnetic disk **12**. The direction of the air flow C coincides with the rotation direction B of the magnetic disk **12**. The slider **42** is arranged with respect to the one surface of the magnetic disk **12** such that the longitudinal direction of the disk facing surface **43** is substantially aligned with the direction of the air flow C. The slider **42** has a leading end **42*a***, which is on the inflow side into which the air flow C flows, and a trailing end **42*b***, which is on the outflow side of which the air flow C flows out.

As illustrated in FIG. **3**, the head portion **44** is formed as a separation type magnetic head, and comprises a magnetic recording head **56** and a reproducing head **54** formed at the trailing end **42*b*** of the slider **42** in a thin-film process.

The reproducing head **54** comprises a magnetic film **50** exhibiting a magneto-resistance effect, and shield films **52*a*** and **52*b*** arranged on the trailing side and the leading side of this magnetic film **50** to sandwich the magnetic film **50**. The respective lower ends of the magnetic film **50**, and the shield films **52*a*** and **52*b*** are exposed at the disk facing surface **43** of the slider **42**.

The recording head **56** is located on the trailing end **42*b*** side of the slider **42** with respect to the reproducing head **54**. As illustrated in FIG. **3**, the recording head **56** comprises a main magnetic pole (a recording magnetic pole) **66** made of a high saturation magnetization material for generating a recording magnetic field perpendicular to the surface of the magnetic disk **12**, a trailing shield (a shield magnetic pole) **68** confronting the trailing side of the main magnetic pole **66** with a gap (a write gap) in between, a recording coil **71** wound around a magnetic circuit (a magnetic core) including the main magnetic pole **66** and the trailing shield **68**, and a microwave oscillator, such as a spin-torque oscillator **74**, forming a part of the disk facing surface **43** between the distal end portion **68*a*** of the trailing shield **68** and a distal end portion **66*a*** which the main magnetic pole **66** has at the disk facing surface **43** side. When a signal is written to the magnetic disk **12**, a recording current is flowed through the recording coil **71** to cause the main magnetic pole **66** to generate a magnetic flux.

The main magnetic pole **66** extends substantially perpendicularly to the one surface of the magnetic disk **12**. The distal end portion **66*a*** is tapered or narrowed down toward the disk surface. The distal end surface of the main magnetic pole **66** is exposed and is flush with the disk facing surface **43** of the slider **42**. In the present embodiment, the width of the distal end portion **66*a*** of the main magnetic pole **66** is substantially the same in length as the track width of the magnetic disk **12**.

The trailing shield **68** is substantially L-shaped, and its distal end portion **68*a*** is formed into an elongated rectangular shape. The distal end surface of the trailing shield **68** is exposed and is flush with the disk facing surface **43** of the slider **42**. The trailing shield **68** is provided to efficiently close a magnetic path with the help of the soft magnetic layer **23** directly under the main magnetic pole **66**. The leading side end surface of the distal end portion **68***a* extends along the track width of the magnetic disk **12**. The leading side end surface faces and substantially parallels the trailing side end surface of the main magnetic pole **66** with a write gap WG in between. It is possible to provide side shields at the respective sides of the main magnetic pole **66** distant from each other in the track width direction. The provision of the side shields makes it possible to reduce a fringe magnetic field affecting to an adjacent truck, resulting in improvement in recording density of the truck width direction.

The trailing shield **68** is coupled through a nonconductive body **67** of SiO_2, for instance, to the main magnetic pole **66** at a position distant from the disk facing surface **43**. The main magnetic pole **66** and the trailing shield **68** are electrically insulated by the nonconductive body **67**.

The recording coil **71** is connected through a wire W_1 to a recording current control circuit **70**. The recording current control circuit **70** is provided at the control circuit board **25** or the board unit **17** or a preamplifier IC arranged at that end of the main FPC **38** that is located at the relay flexible printed circuit board (interconnection member) **35** side. The recording current control circuit **70** comprises an overshoot control circuit **77** and a recording current driving circuit **76** connected to a power supply **82**. The recording current driving circuit **76** supplies a recording current I_W to the recording coil **71** in accordance with a recording signal or meeting the recording pattern applied from the control circuit board **25**. The recording coil **71** magnetizes the main magnetic pole **66** and causes the main magnetic pole **66** to generate a recording magnetic field. When the recording current I_W inverts, the overshoot control circuit **77** controls the overshoot of the recording current in proportion to the driving current of the spin-torque oscillator **74**.

As illustrated in FIG. **3**, the spin-torque oscillator **74** is provided within the write gap WG between the distal end portion **66***a* of the main magnetic pole **66** and the leading side end surface of the trailing shield **68**. The lower end surface of the spin-torque oscillator **74** is exposed, constituting a portion of the disk facing surface **43** of the slider **42**, and is positioned at almost the same height as the distal end surface of the main magnetic pole. Namely, the lower end surface of the spin-torque oscillator **74** is flush with the disk facing surface **43** of the slider **42**, and is positioned almost parallel to the one surface of the magnetic disk **12**.

The spin-torque oscillator **74** comprises a seed layer made of a non-magnetic conductive layer, a spin-injection layer (a first magnetic substance layer) **74***a*, an intermediate layer **74***b*, an oscillation layer (a second magnetic substance layer) **74***c*, and a cap layer made of a non-magnetic conductive layer. Theses layers are successively stacked from the main magnetic pole **66** side to the trailing shield **68** side in the mentioned order. The seed layer is formed to be in contact with the distal end portion **66***a* of the main magnetic pole **66**. The cap layer is formed to be in contact with the leading side end surface of the trailing shield **68**.

The oscillation layer **74***c* is made of such a material that has a soft magnetic property and a large saturation magnetic flux density, namely, Fe or Co or Ni, for instance. The intermediate layer **74***b* is made of a material having a long spin diffusion length, for example, Cu. The spin-injection layer **74***a* is made of, for instance, a Co/Ni artificial lattice which is high in coercivity and high in spin polarization rate. It is also possible to make the spin-injection layer **74***a* from a material having a smaller coercivity than the gap magnetic field which is generated during recording. It should be noted that the configuration is not limited to the above configuration in which the spin-injection layer **74***a*, the intermediate layer **74***b*, and the oscillation layer **74***c* are stacked in this order from the main magnetic pole side **66**, but it is possible to stack the oscillation layer, the intermediate layer, and the spin-injection layer in this order from the main magnetic pole side **66**.

The spin-torque oscillator **74** is connected through the main magnetic pole **66**, the trailing shield **68**, and wires W_2 to a spin-torque oscillator (STO) driving current control circuit **80**. The STO driving current control circuit **80** is provided at the control circuit board **25** or the board unit **17** or a preamplifier IC arranged at an end of the relay flexible printed circuit board (interconnection member) **35** side of the main FPC **38**, and is connected with the power supply **82** and the overshoot control circuit **77**. The STO driving current control circuit **80** applies voltage from the power supply **82** to the main magnetic pole **66** and the trailing shield **68** under the control of the control circuit board **25**, thereby causing a driving current I_{STO} to serially pass through wire W_2, the main magnetic pole **66**, the spin-torque oscillator **74**, and the trailing shield **68**. Namely, the STO driving current control circuit **80** causes a direct current to flow in the direction of the film thickness of the spin-torque oscillator **74**. The passage of current rotates the magnetization of the oscillation layer **74***c* of the spin-torque oscillator **74**, which makes it possible to generate a high-frequency magnetic field (a microwave). Thus, the spin-torque oscillator **74** applies the high-frequency magnetic field to the recording layer of the magnetic disk **12**, and decreases the coercivity of the recording layer.

FIGS. **4**A, **4**B, and **4**C are graphs illustrating (A) a recording current waveform, (B) an STO driving current waveform, and (C) the oscillation behavior of the spin-torque oscillator **74**, all exhibited under the conditions that the overshoot S_1 of the recording current I_W is set to 25 mA, which is ten times as great as the driving current of the STO driving current, when the recording current I_W is set to 40 mA and the STO driving current I_{STO} is set to 2.5 mA.

The recording current waveform exhibits such a waveform that the overshoot current will be superposed on the recording current waveform, whenever the recording current waveform reverses in polarity, and thereafter the recording current waveform returns to a fixed current of 40 mA, which is the set value. The overshoot current S_1 is so controlled as to be 25 mA. Therefore, the maximum value which the recording current waveform exhibits after every inversion has a peak of 65 mA. At this moment, the STO driving current waveform exhibits the set value of 2.5 mA at those portions where the recording current I_W will not reverse. However, the superposition of the crosstalk noise (current) occurring between wires W_1 and W_2 when the recording current reverses causes a level fluctuation between a maximum absolute value of about 3 mA and a minimum absolute value of about 2.3 mA. Concerning the oscillation behavior of the spin-torque oscillator **74** at the moment, it promptly oscillates after the recording current I_W has reversed and the oscillation delay can hardly occur after the recording current has reversed. It should be noted that the overshoot control circuit **77** controls the negative side undershoot current S_2 in common with the positive side overshoot current S_1 in the present embodiment.

FIGS. **5**A, **5**B, and **5**C illustrate as a comparative example (A) a recording current waveform, (B) an STO driving current waveform, and (C) the oscillation behavior of the spin-torque oscillator, all exhibited under the conditions that the STO driving current control circuit **80** and the overshoot control circuit **77** are disconnected and overshoot of the recording current I_W will be prevented. The recording current I_W and the STO driving current I_{STO} are respectively set to 40 and 2.5 mA.

As illustrated in FIGS. **5**A, **5**B, and **5**C, the recording current I_W in the comparative example exhibits a current waveform that scarcely has overshoot at the time of polarity inversion. The STO driving current waveform shows that the crosstalk noise between wires W_1 and W_2 is slightly superposed whenever the recording current I_W reverses in polarity, but its magnitude is no greater, than about 0.1 mA. It will be understood that the oscillation behavior of the spin-torque oscillator **74** at that moment exhibits that the oscillation intensity gently rises and the oscillation frequency gradually shifts from a low value to a high value. Therefore, it will be understood that it takes time for a high-frequency magnetic field to occur after the reversal of the recording magnetic field in the comparative example.

As having been explained above, the magnetic disk apparatus in the present embodiment makes it possible to cause the spin-torque oscillator **74** to promptly oscillate without incurring delay in oscillation after the recording current has reversed through the provision of the overshoot control circuit **77**, which adjusts the overshoot current in proportion to the driving current of the spin-torque oscillator **74** whenever the recording current I_W reverses. Therefore, the spin-torque oscillator will oscillate immediately after the recording current inversion even in the case where the transfer rate increases and the recording frequency becomes high, achieving making a favorable recording with the assistance of a stable high-frequency.

FIG. **6** illustrates the relationship between the oscillation intensity and the oscillation frequency in a case where the oscillation behavior of the spin-torque oscillator is measured under the condition that the STO driving current I_{STO} is changed. The spin-torque oscillator **74** used here was set to have a resistance of 50Ω, and the measurement was carried out by changing the STO driving current I_{STO} from 1.2 to 4 mA.

The graph indicates that the drive voltage range where the peak intensity will be high and the oscillation frequency will be stable is about 100 to 180 mV. Here, let the drive voltage be 140 mV, which is the midpoint of the drive voltage range where a stable oscillation will be obtained, then the range where a stable oscillation will be obtained will be almost a rage of 140 mV (2.5 mA)±30%. Therefore, in order to maintain a stable oscillation even if the crosstalk noise between the wires is superposed onto the STO driving current I_{STO}, the components of the superposition (current) should be confined to ±30% of the set driving current. A deviation from this range causes an oscillation frequency to deviate or prevents the sufficient oscillation intensity.

As having been explained above, the present embodiment makes it possible to obtain a magnetic disk apparatus that makes faster and stable microwave assisted magnetic recordings.

Now, an HDD related to another embodiment will be explained. In the following explanation of another embodiment, those portions that are the same as those in the first embodiment will be given the same reference numerals as the already explained portions and their detailed explanation will be omitted. The detailed explanation will be mainly given to those that are different from the first embodiment.

Second Embodiment

FIG. **7** is a block diagram of an HDD in a second embodiment schematically illustrating the recording current control circuit of a recording head and the spin-torque oscillator driving current control circuit.

In the second embodiment, the HDD is configured to separately control a positive side overshoot current and a negative side undershoot current of the recording current I_W at the time of polarity inversion. As illustrated in FIG. **7**, the HDD comprises the recording current control circuit **70**, which supplies the recording current through wires W_1 to the recording coil **71** of the magnetic head, and the spin-torque oscillator driving current control circuit **80**, which supplies the driving current through wires W_2 to the spin-torque oscillator (STO).

The recording current control circuit **70** comprises a recording current driving circuit **76**, which is connected to a power supply **82**, an overshoot control circuit **77**, which controls the overshoot current S_1 in proportion to the STO driving current, and an undershoot control circuit **90**, which controls the undershoot current S_2 in proportion to the STO driving current. The overshoot control circuit **77** comprises a first amplitude control circuit **77***a*, which adjusts the amplitude of the overshoot current, and a first period control circuit **77***b*, which controls a sustaining period (duration) T_1 of the overshoot current. In the same way, the undershoot control circuit **90** comprises a second amplitude control circuit **90***a*, which adjusts the amplitude of the undershoot current, and a second period control circuit **90***b*, which controls a sustaining period (duration) T_2 of the undershoot current. Whenever the recording current reverses, the recording current control circuit **70** switches between the overshoot control circuit **77** and the undershoot control circuit **90**, thereby controlling the recording current.

FIGS. **8**A and **8**B are graphs illustrating (A) a recording current waveform, and (B) an STO driving current waveform, both exhibited under the conditions that the recording current I_W is set to 40 mA and the STO driving current is set to 2.5 mA. In the case of the undershoot current of the recording current I_W, a crosstalk noise (current) is superposed onto the spin-torque oscillator (STO) driving current I_{STO} and produces the undershoot current which is followed by ringing. It is the return part of the ringing that contributes toward giving a boost to a spin-torque oscillator. Therefore, it is preferable that the undershoot current S_2 is set greater than the overshoot current S_1.

A crosstalk noise (current) causing the undershoot current upon its superposition contributes toward the lowering the STO driving current I_{STO}. Therefore, the spin-torque oscillator **74** will not be damaged even if the undershoot current S_2 increases. However, the oscillation boosting effect will be delayed when the ringing following the undershoot current is delayed. Therefore, it is preferable that the sustaining period (the duration) T_2 of the undershoot current is set shorter than the sustaining period (the duration) T_1 of the overshoot.

The recording current control circuit **70** comprises an overshoot control circuit (for coping with a positive polarity) **77** and an undershoot control circuit (for coping with a negative polarity) **90**, and selectively uses them in accordance with the direction of the recording current. The first amplitude control circuit **77***a* of the overshoot control circuit **77** controls the amplitude of the overshoot current (an amount exceeding the fixed state) S_1 in such a manner that the crosstalk noise (current), which causes the overshoot current and is superposed onto the STO driving current I_{STO}, should be ±30% of the set STO driving current.

The second amplitude control circuit **90***a* of the undershoot control circuit **90** sets the amplitude of the undershoot current (an amount lower than the fixed state) S_2 to be, for instance, 40 to 60% greater than the amplitude of the overshoot current S_1 whenever the recording current I_W reverses. Furthermore, the second sustaining period control circuit **90***b* of the undershoot control circuit **90** sets the sustaining period T_2 of the undershoot current to be shorter than the sustaining period T_1 of the overshoot current, and it is desirable to set the T2 to, for instance, ⅔ of the T_1.

Thereby the component of increasing the STO driving current I_{STO} in the case of overshoot of the recording current I_W will be substantially the same as the component of increasing the STO driving current I_{STO} in the case of undershoot, resulting in the favorable spin-torque oscillation regardless of the direction of the recording current.

The remaining structures of the HDD in the second embodiment are the same as those in the aforementioned first embodiment. The second embodiment structured as described above makes it possible to obtain a magnetic disk apparatus that makes faster and stable microwave assisted magnetic recordings than the recording head of the first embodiment

In the second embodiment, it is possible to set the recording current I_W in such a manner that the positive current level L_1 and the negative current level L_2 are different from each other, namely,

$$L_1>L_2 \text{ or } L_1<L_2.$$

While certain embodiments have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the inventions. Indeed, the novel embodiments described herein may be embodied in a variety of other forms; furthermore, various omissions, substitutions and changes in the form of the embodiments described herein may be made without departing from the spirit of the inventions. The accompanying claims and their equivalents are intended to cover such forms or modifications as would fall within the scope and spirit of the inventions.

For instance, a place where the spin-torque oscillator is located is not limited to the trailing side of the main magnetic pole, but may be at the leading side of the main magnetic pole. The magnitudes of the recording current, driving current, overshoot current and undershoot current of the recording current, and the sustaining periods are not limited to the values illustrated in the above embodiments, but may be changed as deemed fit.

What is claimed is:

1. A magnetic disk apparatus comprising:

a main magnetic pole configured to apply a recording magnetic field to a recording layer of a recording medium;

a recording coil configured to magnetize the main magnetic pole;

a spin-torque oscillator, configured to generate a high frequency magnetic field, adjacent to the main magnetic pole and close to a medium-facing surface opposite the recording medium;

a recording current control circuit configured to supply a recording current to the recording coil;

a driving current control circuit configured to supply a fixed driving current to the spin-torque oscillator; and

an overshoot control circuit configured to control, in proportion to a magnitude of the driving current, overshoot current of the recording current occurring after the recording current has reversed.

2. The magnetic disk apparatus of claim **1**, which further comprises:

a first wire configured to connect the recording coil and the recording current control circuit; and

a second wire configured to connect the spin-torque oscillator and the driving current control circuit,

the driving current supplied to the spin torque oscillator including a portion higher than the absolute value of the fixed driving current because of level fluctuation caused by crosstalk from the first wire to the second wire at a moment of applying the recording current.

3. The magnetic disk apparatus of claim **2**, wherein the overshoot control circuit is configured to control the overshoot current of the recording current in such a manner that a level fluctuation of the driving current caused by the crosstalk is within ±30% of the fixed driving current.

4. The magnetic disk apparatus of claim **1**, wherein the recording current control circuit comprises the overshoot control circuit configured to control in proportion to the magnitude of the driving current the overshoot current occurring after the recording current has reversed to a positive current; and an undershoot control circuit configured to control, in proportion to the magnitude of the driving current, undershoot current occurring after the recording current has reversed to a negative current.

5. The magnetic disk apparatus of claim **4**, wherein the undershoot control circuit is configured to set the undershoot current greater than the overshoot current.

6. The magnetic disk apparatus of claim **5**, wherein the overshoot control circuit comprises a first sustaining period control circuit configured to control a sustaining period of the overshoot current, and the undershoot control circuit comprises a second sustaining period control circuit configured to set sustaining period of the undershoot current shorter than the sustaining period of the overshoot current.

7. The magnetic disk apparatus of claim **4**, wherein the overshoot control circuit comprises a first sustaining period control circuit configured to control a sustaining period of the overshoot current, and the undershoot control circuit comprises a second sustaining period control circuit configured to set a sustaining period of the undershoot current shorter than the sustaining period of the overshoot current.

8. The magnetic disk apparatus of claim **2**, wherein the recording current control circuit comprises: the overshoot control circuit configured to control in proportion to the magnitude of the driving current the overshoot current occurring after the recording current has reversed to a positive current; and

an undershoot control circuit configured to control, in proportion to the magnitude of the driving current, undershoot current occurring after the recording current has reversed to a negative current.

9. The magnetic disk apparatus of claim **8**, wherein the undershoot control circuit is configured to set the undershoot current greater than the overshoot current.

10. The magnetic disk apparatus of claim **9**, wherein the overshoot control circuit comprises a first sustaining period control circuit configured to control a sustaining period of the overshoot current, and the undershoot control circuit comprises a second sustaining period control circuit configured to set a sustaining period of the undershoot current shorter than the sustaining period of the overshoot current.

11. The magnetic disk apparatus of claim **3**, wherein the recording current control circuit comprises: the overshoot control circuit configured to control in proportion to a magnitude of the driving current the overshoot occurring after the recording current has reversed to a positive current; and

an undershoot control circuit configured to control, in proportion to the magnitude of the driving current, undershoot current occurring after the recording current has reversed to a negative current.

12. The magnetic disk apparatus of claim **11**, wherein the undershoot control circuit is configured to set the undershoot current greater than the overshoot current.

13. The magnetic disk apparatus of claim **12**, wherein the overshoot control circuit comprises a first sustaining period control circuit configured to control a sustaining period of the overshoot current, and the undershoot control circuit comprises a second sustaining period control circuit configured to set a sustaining period of the undershoot current shorter than the sustaining period of the overshoot current.

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